

# Correlations between Dynamic Penetrometer Light and Cone Penetration Tests in Intermediate Soils: a Statistical Comparison

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**ABSTRACT:** This paper presents a statistical approach to evaluate the variation between current correlation models of Dynamic Penetrometer Light (DPL) against Piezocone Penetration Test (CPT) results. Work methodology included the execution of three DPL tests and three CPT at the left bank of Ave River (Vila do Conde, Portugal) and the calculation of the cone resistance through DPL correlations. Besides, addressed a comparison of the values obtained from such correlations and the measured values by the CPTu device by the measures profiles technique. Statistical analyses allowed identifying the level of parallelism, horizontality and coincidence between results in depth. From the results, it was found that the existing correlations between DPL and CPT are not accurate for intermediate soils and it is necessary to develop a new correlation for this type of materials.

**KEY WORDS:** cone resistance, in situ tests, repeated measures profiles, statistical analysis.

## 1 INTRODUCTION

Soil identification on the field includes several testing techniques. One of the most popular of such techniques is cone penetration test (CPT). This test provides an in situ characterization of the soil almost continuously. Besides, the CPT has a strong theoretical background, which allows identifying physical and mechanical soil properties.

However, some countries do not use the CPT for all its construction projects. For this reason, the literature presents models to correlate results between different field techniques. Such correlations relate CPT values with standard penetration test (SPT), pressuremeter test (PMT) dilatometer test (DMT) and light weight dynamic penetrometer test (DPL) (Ruge *et al.*

2018). Hamid (2015) presented a brief overview of the DPL and its historical development, correlations with soil parameters, and relationship with different instruments. Lingwanda *et al.* (2015) compared, statically, DPL test results with CPT to facilitate the transformation of DPL data and increase its applicability in Tanzania. Dos Santos & Bicalho (2017) provides some insights about DPL-CPT correlations and the proposed new correlations between such tests for the city of Vitoria (Brazil).

The aim of this paper is to present a statistical comparison between the dynamic cone resistance ( $q_d$ ) obtained from the energy transformation of the DPL results against the cone resistance ( $q_c$ ) measured through CPT device. Both types of tests were performed very close to each other the shipyard on the left bank

of Ave River (Vila do Conde, Portugal). The statistical assessment addressed the analysis of repeated measures profiles (RMP) and the linear regression assessment. Therefore, the document structure is the following. The first section corresponds the materials and method of the work research, which includes a description of the study site, DPL test and RMP technique. The second section presents the tests results and the statistical analysis. Finally, the third section shows the conclusions of this work.

## 2 MATERIALS AND METHODS

### 2.1 Site description

The tests were performed in the left bank of Ave River, near the city of Vila do Conde in north Portugal, where the new shipyards of “Vila do Conde” were installed. This area is very close to the river mouth, which means that it suffers from the tidal influence. The tides in this region of the Atlantic coast are very wide frequently achieving 4 m of water height between the low and the high tide. Such aspect had an important effect not only for the tests execution but also in the water table evaluation.

On another hand, this area was the deposition place of dredged sediments from Ave River in the past due to the current need of assuring river navigability. Therefore, the soil formation of this site was a product of the deposition of fluvial sediment and so the selection of this area. Figure 1 displays the location of the points of exploration.



Figure 1. Identification of the three test points (adapted from Google Earth).

### 2.2 DPL test

DPL test is a field technique based on the same principle of the SPT test. Hence its test procedure involves the falling of a hammer from a specific height. However, unlike SPT device, DPL device has a cone instead of a sampler. The test measures the effort required to drive the cone through the soil and then obtain resistance values that correspond to the soil mechanical properties. Besides, it allows visualizing the variation of penetration resistance with depth. Figure 2 presents a schematic description of DPL components.

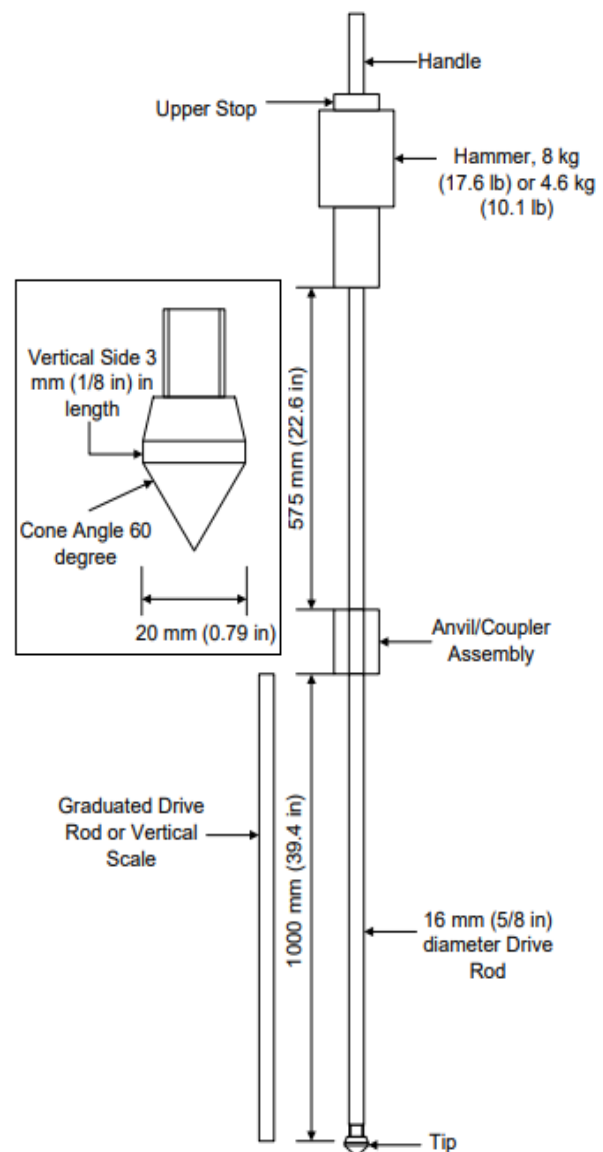


Figure 2. DPL device (after Edil & Benson, 2005).

The results of this test are represented by the number of blows to achieve 10 cm penetration ( $N_{10}$ ). The main limitation of DPL is that in higher depths, the initial energy is dissipated along the tubing and the device does not advance. For that reason, the maximum depth of the test is 8 m and rarely reaches firm layer or bedrock. Furthermore, the test could be rejected if  $N_{10} > 100$ .

Usually, DPL results are correlated to found its equivalent values with other tests (as the CPT) and allow obtaining a better identification of the ground. Moreover, DPL results complement CPT results and provide additional information about the mechanical behaviour of the soil at different depths (Martins & Miranda, 2003). The International Organization for Standardization, in its standard procedure ISO 22476-2 (2005), presents a model to transform the DPL results into dynamic cone resistance ( $q_d$ ). Such model is presented in equation 1. The results depend only on the energy of the hammer falling (specific energy) in each blow per unit area of the nozzle section. Equation 1 presents the Dutch formula, where  $q_d$  represents the resistance values in Pa;  $m$  is the mass of the hammer in kg;  $g$  is the acceleration of gravity in N / kg;  $h$  is the fall height of the mass (m);  $A$  is the base area of the cone in  $m^2$ ;  $e$  corresponds to the mean penetration; and  $m'$  is the total mass of rod, hammer and guide rods in kg.

$$q_d = \frac{m^2}{m+m'} \cdot \frac{ghN_{10}}{Ae} \quad (1)$$

Nowadays, it is common to correlate  $q_d$  with the  $q_c$ , since the CPTu tests are not used in many countries and the DPL tests are fast and economic. Nevertheless, the models obtained to correlate such results are not theoretically well-founded because the procedures are conceptually different (the DPL is dynamic and the CPT is static). The above indicates a different soil behaviour during the execution of one or another. Viana da Fonseca (1996) introduces a model to correlate the  $q_d$  values with the  $q_c$  values (equation 2).

$$K_e = q_c/q_d \quad (2)$$

Viana da Fonseca (1996) affirmed that in homogeneous soils the value of  $K_e = 1$  and Dos Santos & Bicalho (2017) indicated such values varies from 1.3 to 2.5 in sands.

### 2.3 Repeated measures profiles

The repeated measures profiles (RMP) is a statistical technique, which analyses the mean variation of the values measured at the same level (Molina-Gómez, 2017). Furthermore, this technique allows estimating the variation of a response variable subjected to different treatments. Tabachnick & Fidell (2013) mention that the data set may come from a dependent variable measured several times under the same level; for example, data collected at the same depth.

RMP technique focuses mainly on the comparison of variances. Thereby, it evaluates if the mean vectors of the measured values are equal (Friendly, 2010). To establish the above approach is necessary to evaluate three null hypotheses (Davis, 2002). Those hypotheses are parallelism, flatness and coincidence. Harrar & Kong (2016) affirm that such hypotheses seek to respond the following questions: (i) whether there is the interaction effect between the measurements and within-subject factors (ii) whether there is a between-subject factor effect, and (iii) whether there is a within-subject factor effect. Figure 3 presents a graphical representation of the null hypothesis.

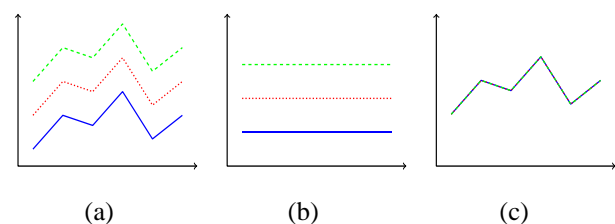


Figure 3. Null hypotheses representation (Molina-Gómez, 2017): (a) parallelism; (b) flatness; (c) coincidence.

Molina-Gómez, Moreno Anselmi, & Arévalo-Daza (2016) recompiled the theoretical background of RMP and presented procedure to analyse the data in **RStudio** by using the *profileR* package (Bulut & Desjardins, 2017). In this work such procedure was applied.

### 3 RESULTS

#### 3.1 Field test

Three different DPL and CPT tests at 4.5 m depth were performed. The separation between both types of tests was of 2 m. Figure 4 presents the DPL results. These results allowed obtaining a previous identification of the soil and verifying that does not exist a layer, which could cause damages to the CPT device. Hence, the DPL tests guaranteed a preliminary inspection of the soil before of the CPT execution.

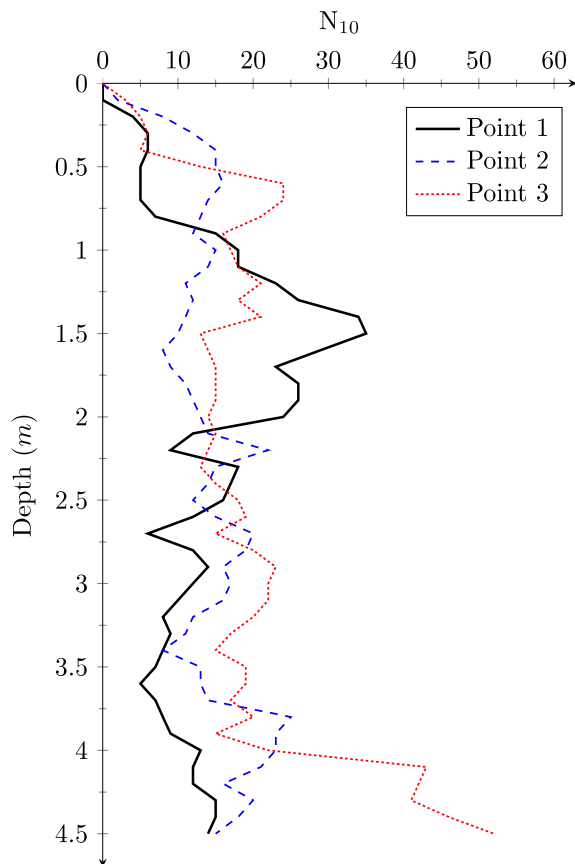


Figure 4. Number of blows for the 3 points

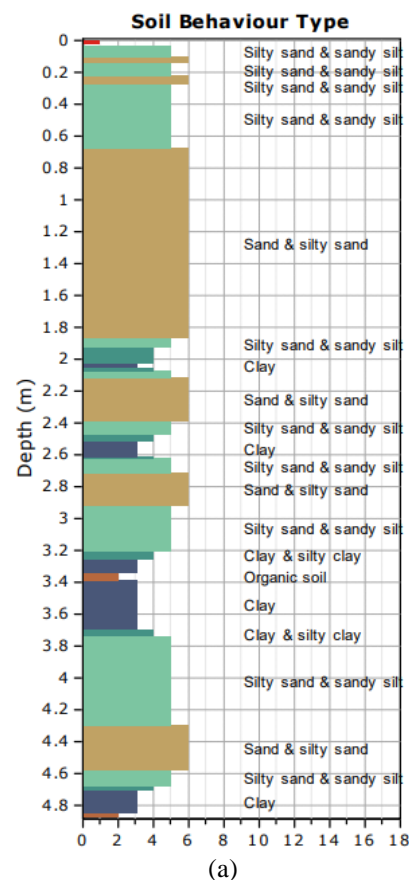
By other hand, CPT tests were interpreted according to the unified approach proposed by Robertson (2009). The calculation routine was the proposed by Rios, da Fonseca, Cristelo, & Pinheiro (2018) which involved the basic CPT parameters (cone resistance,  $q_c$  and sleeve friction,  $f_s$ ). The Robertson chart is based on the classification of normalized soil behaviour type (SBTn) zones by means of the  $I_c$  parameter (equation 3). Such parameter represents the

radius of concentric circles that define the boundaries of soil types.

$$I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 0.22)^2]^{0.5} \quad (3)$$

Where  $Q_t$  is the normalized cone penetration resistance and  $F_r$  is the normalized friction ratio.

Rios et al. (2018) explains what the boundary represented by  $I_c = 32$  represents the lower boundary for most sand like ideal soil and is like SBTn zones 4 and 5 for normally consolidated soils. The boundary I ( $I_c = 22$ ) represents the upper boundary for most claylike ideal soils and is like the original boundary between SBTn zones 3 and 4 for normally consolidated soils. The region represented by  $22 < I_c < 32$  is defined as “transitional soil” to represent soils that can have a behaviour somewhere between that of either sandlike or claylike ideal soil. For these soils, an expected partial drained behaviour may be expected during a CPT test, and so these soils are also called as intermediate soils. Figure 5 presents the SBTn results.



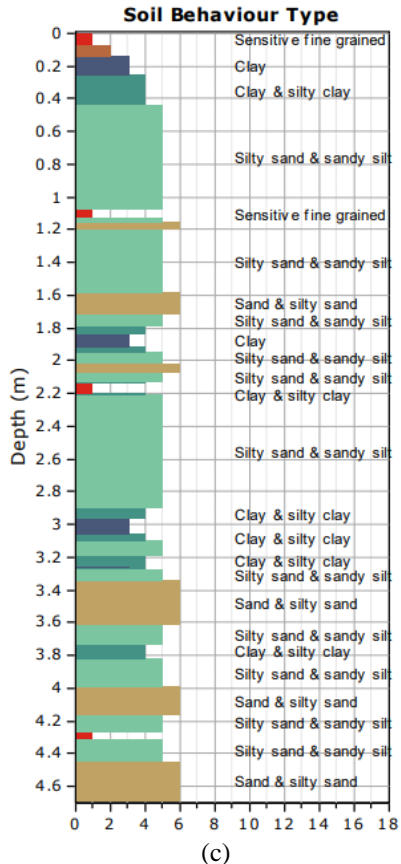
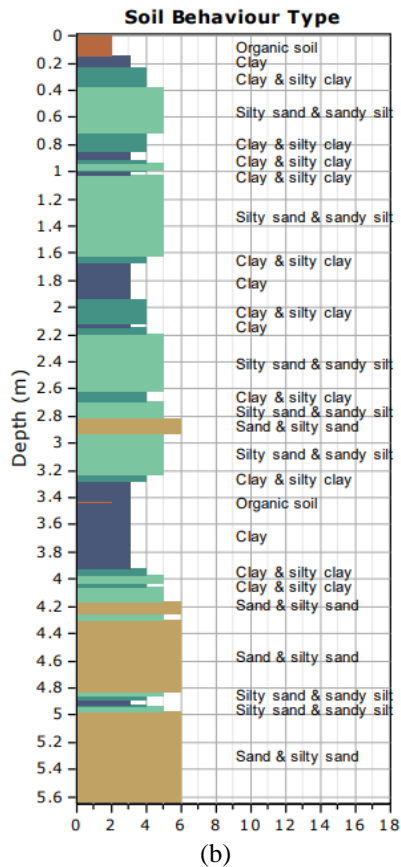


Figure 5. Soil classification based on SBTn: (a) point 1; (b) point 2; (c) point 3.

Figure 5 shows the presence of transitional soils between 1.8 and 4.2 m depth at all points. Intermediate materials are the silty soils and the mixtures of sand and clay. The geotechnical behaviour of sands and clays is already well understood by different constitutive models. However, intermediate soils have different tendencies. The behaviour in this type of materials can be transitional between sands and clays or can exhibit unique behaviour, which differs from both granular and fine soils. Hence, the intermediate soils may exhibit, simultaneously, properties of sand and clay. In addition, the correlations between DPL and CPT do not present an acceptable fitting for particular kind of soil.

In addition, it was recuperated a soil sample from point 2 at 4 m depth. This sample was taken to the laboratory in order to obtain its physical characteristics (Table 1) and grain size distribution (Figure 6). Results validated that the material at such depth is an intermediate soil, due to according to the USCS is classified as Silty Sand (SM).

Table 1. Geotechnical properties of the intermediate soil.

Geotechnical Property	Value	Unit
Specific gravity	2.66	-
Plastic limit	NP	%
Liquid limit	NP	%
D <sub>60</sub>	0.40	mm
D <sub>50</sub>	0.35	mm
D <sub>30</sub>	0.25	mm
D <sub>10</sub>	0.02	mm
Fines fraction (sieve N° 200)	12.77	%
Uniformity coefficient	16.83	-
Curvature coefficient	7.41	-

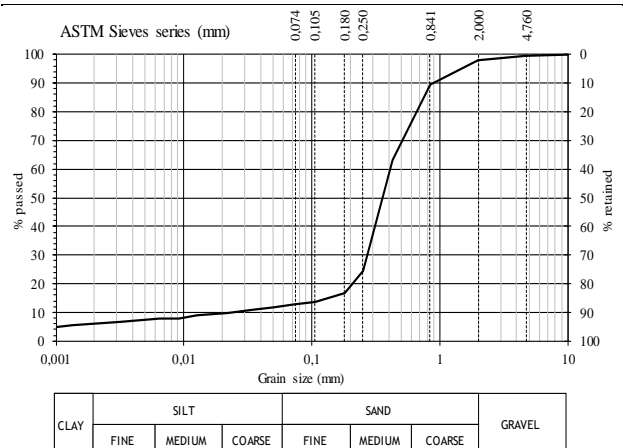


Figure 6. Grain size distribution of the intermediate soil.



### 3.2 Statistical Analyses

Figure 7 shows the profiles of the cone resistance (CR) between both field tests. Profiles data were obtained from the computation of equation 1 ( $q_d$ ) and direct records of CPT ( $q_c$ ). Profiles displayed a good tendency of the correlation is fitted with the real values along the depth in all points.

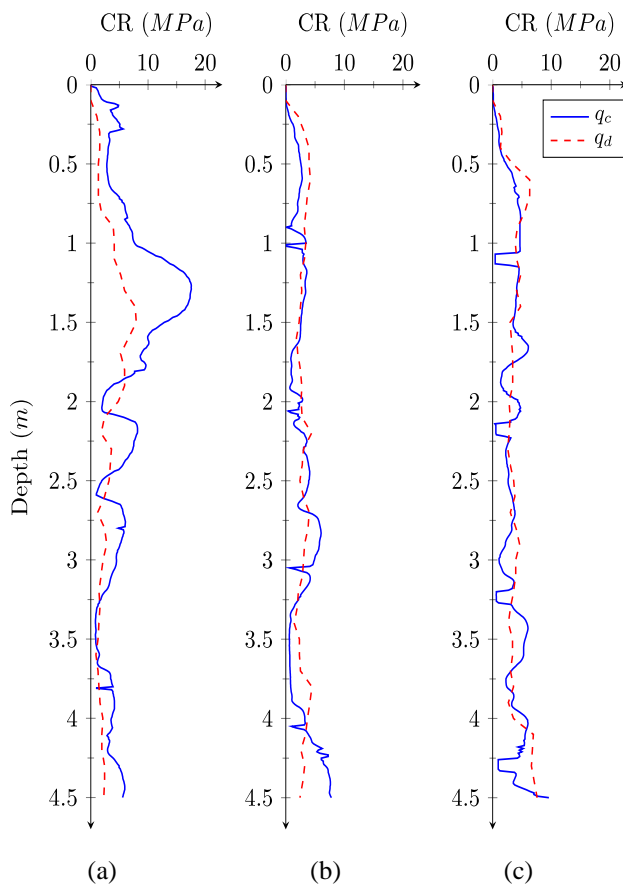


Figure 7. RMP of cone resistances: (a) point 1; (b) point 2; (c) point 3.

Table 2 presents the analysis of RMP results by the evaluation of the three null hypotheses of such statistical technique. It was established if the profiles of cone resistance are parallel, flatness or coincident under a significance level of 95% ( $\alpha=0.05$ ) according to the values obtained from *profileR* results. The value of  $\alpha$  was selected according to established in the experiments design literature by Kuehl (2000) and Ramachandran & Tsokos (2009). The analysis results were based on the  $p$ -value criterion.

In Table 2 it was evidenced that the  $p$ -values are less than the  $\alpha$  value selected. Therefore, it exist statistical evidence to reject all null hypotheses (Habiger, 2015; Wackerly, Mendenhall, & Scheaffer, 2008) and validate that the profiles in all tests points are parallel, flatness and coincident.

Table 2. Analysis of RMP results.

Point	$H_0$	$p$ -value
1	Parallelism	7.03e-21
	Flatness	2.02e-16
	Coincidence	1.46e-24
2	Parallelism	4.05e-18
	Flatness	8.99e-4
	Coincidence	8.71e-28
3	Parallelism	1.55e-20
	Flatness	2.12e-16
	Coincidence	6.86e-27

Due to the null hypotheses were non-rejected and the profiles of both tests are not transposed, it was evaluated the correspondence between the  $q_d$  and  $q_c$  values. Such evaluation was made through the linear regression method with an intercept equal to zero as suggest Dos Santos & Bicalho (2017).

This analysis allowed the calculation of the  $K_e$  value presented in equation 2. Figure 8 shows the regression results. Results presented coefficients of correlation lower than 0.60, which indicates that the linear models do not represent, acceptably, the correlation DPL and CPT in all points. Moreover, the parameters of the linear models showed that points 1 and 2 have  $K_e$  values within the range presented by Dos Santos & Bicalho (2017). However, for point 3 such value is not included in the [1.3-2.5] range, conversely to points 1 and 2 since these points have fewer layers of silty sand and sandy silt. Nevertheless, in point 3 small differences were observed between  $q_d$  and  $q_c$  profiles as observed in Figure 7.

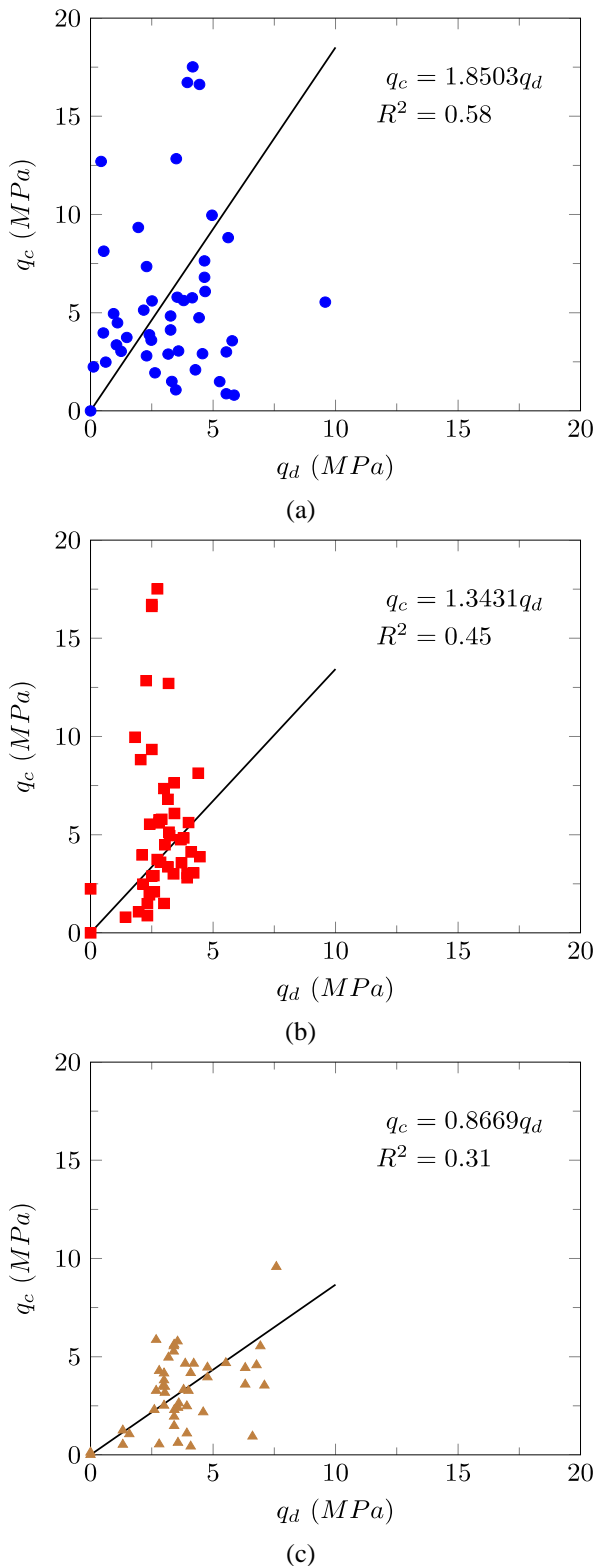


Figure 8. Linear regression results: (a) point 1; (b) point 2; (c) point 3.

On the other hand, it was assessed the descriptive statistics in order to identify the range of  $K_e$  values in this type of soil. Table 3

summarizes the descriptive statistics and Figure 8 displays the box plots with these parameters. Results did not indicate significant differences between mean and median values. In addition, six outliers (four in point 1, one in point 2 and one in point 3) were observed. Such outliers are in the zone of intermediate soils (at 2-4 m depth), except the value at 0.1 m in point 1, which is  $K_e=0$  at the start of the tests. Box plots indicates differences between  $K_e$  values obtained from clean sand and intermediate soils.

Table 3. Descriptive statistics.

Point	Descriptive	Value
1	Mean	1.97
	Median	1.97
	Standard deviation	1.05
2	Mean	0.96
	Median	0.86
	Standard deviation	0.69
3	Mean	0.87
	Median	0.83
	Standard deviation	0.50

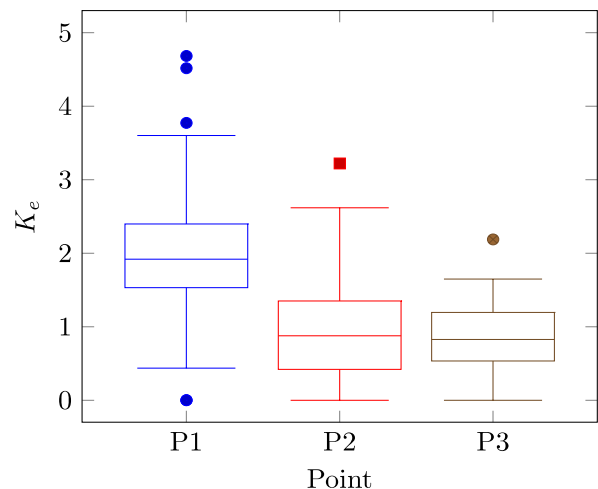


Figure 9. Box plots of  $K_e$  results.

Due to the differences of  $K_e$  values obtained in regression models, such value was calculated again only for the transitional layers. Figure 9 shows the results of the new analysis. It was found different values of  $K_e$ , which indicated that the range presented by Dos Santos & Bicalho (2017) is not appropriate for transitional soils. In addition, the coefficients of correlation were lower than 0.20 and lower than in the first regression calculation. Correlation results verified that there is no linear correspondence

between  $q_d$  and  $q_c$  values for intermediate soils. In this way, it confirmed that the linear model is not accurate to correlate DPL with CPT in this type of material.

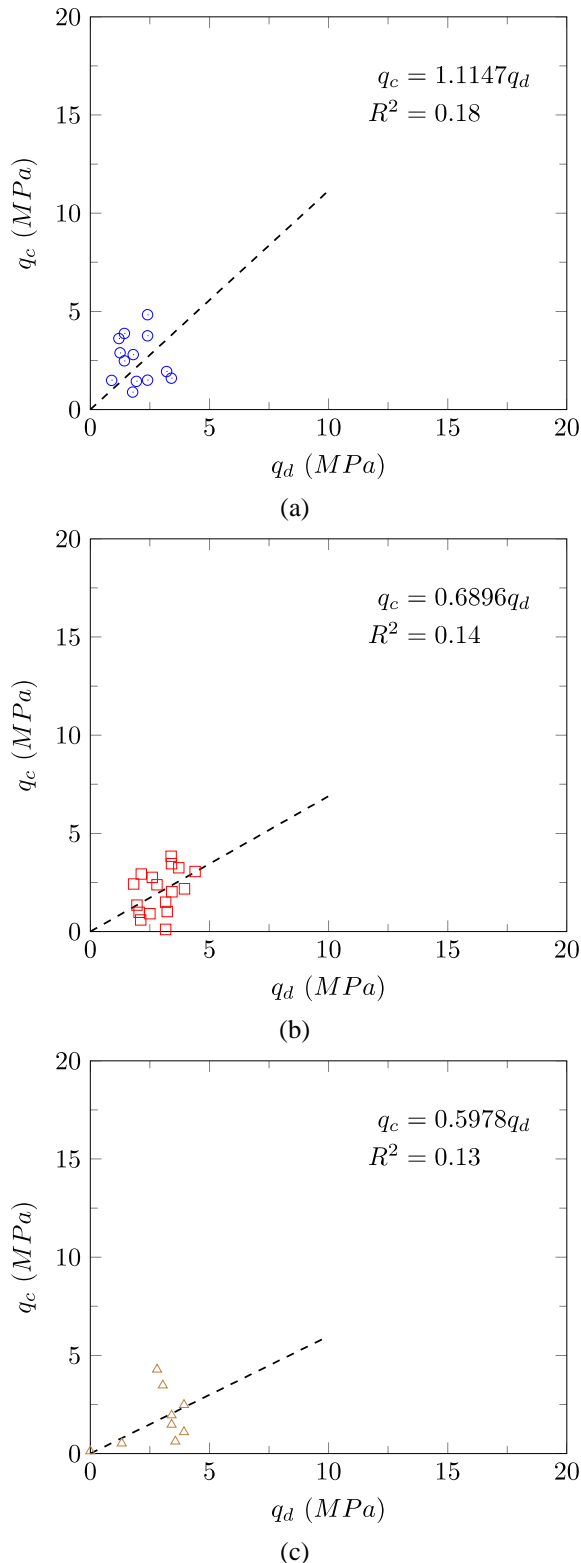


Figure 9. Linear regression results in intermediate soil layers: (a) point 1; (b) point 2; (c) point 3.

#### 4 CONCLUSIONS

This paper addressed a statistical comparison between the results of two different field tests in intermediate soils. In this study were analysed correlations between DPL and CPT tests. Practical and academic conclusions are the following:

- It was identified an intermediate soil product of fluvial sediments. Based on the soil classification based on SBTn (Robertson, 2009), the soil presented dilative transitional behaviour of silty sand to silty clay. Such materials can have characteristics typical of granular and fine grained soils at the same time. In addition, the correlation analysis revealed that correlation values between both tests are not within the typical values reported in the literature for granular materials.
- A graphical statistical approach for the two different types of field tests, DPL and CPT, was implemented. The analysis of RMP allowed estimating parallelism, flatness and coincidence level between test records. It was found the symmetry, stability and coincidence of the profiles under a confidence level of 95%. Therefore, the  $q_d$  and  $q_c$  profiles in all points are parallels, flatness and equally from a statistical point of view. It was found that the DPL is a good preliminary soil recognition method before performing the CPTu, even though there are differences between the execution of both tests.
- The records between DPL and CPT tests were compared. Results showed that for intermediate soils the correlation between  $q_d$  and  $q_c$  is not described by linear models. In the layers of clean sands, the  $K_e$  values are acceptable, whereas in the transitional soil layers the  $K_e$  values are more disperse than the values for sands. In addition, the coefficients of correlation were not suitable to establish a correlation between  $q_d$  and  $q_c$  results obtained from DPL and CPT tests. Hence, it is necessary to propose new alternative models to estimate the results of such among tests, which involve the particular characteristics of the intermediate soils.



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